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FIELD STUDIES OF SAND PATCH INITIATION PROCESSES ON THE NORTHERN MARGIN OF THE NAMIB SAND SEA

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ABSTRACT

Field studies of protodunes (sand patches) on the northern margin of the Namib Sand Sea suggest that they are initiated in a zone of spatially and temporally fluctuating winds on the distal plinth of one of the south–north linear dunes and migrate northward across granule to gravel substrates. The sand patches disperse as surface roughness increases in the net migration distance. Dispersal of the sand patches is also constrained by sand supply. These studies suggest the importance of interactions between surface and aerodynamic roughness, transport thresholds, and sand supply in the initiation of dunes.

KEY WORDS aeolian processes; sand patch initiation; Namib Desert; aerodynamic roughness

INTRODUCTION

The conditions that lead to dune initiation and the processes involved therein are poorly understood and little studied, but they are of major importance to understanding how dunes and dune patterns develop. Dune initiation involves localized deposition leading to bedform nucleation, which will then fix a pattern that can propagate downwind (Wilson, 1972). Deposition implies a reduction in the local sediment transport rate as a result of flow deceleration in the lee of obstacles (e.g. Hesp, 1981; Tsoar, 1989), changes in surface roughness as a result of vegetation and variations in surface particle size, or variations in microtopography (slope changes, relict bedforms) (Bagnold, 1941; Cooper, 1958; Jäkel, 1980; Kocurek *et al.*, 1992). There are few studies of the initiation and early development of dunes. Cooper (1958), Jäkel (1980) and Kocurek *et al.* (1992) have described the development of barchans and transverse ridges from thin sand patches with no flow separation in their lee to small dunes with lee-side flow separation, but only Kocurek *et al.* (1992) have documented the initiation of sand patches where changes in aerodynamic roughness or microtopography cause a reduction in near-surface wind speeds.

Some parts of the interdune areas on the northern margin of the Namib Sand Sea are characterized by areas of thin sand sheets and sand patches 1 to 10 m across and a few centimetres thick that appear to be protodunes. This paper documents their morphology, distribution and short-term dynamics and examines sand patch distribution in relation to changes in surface roughness and boundary-layer winds.

THE STUDY AREA

The study area is located on the margin of the Namib Sand Sea, just south of the Kuiseb River valley that forms its northern edge. In the area south of Gobabeb (Figures 1 and 2), the large south- to north-trending complex linear dunes that characterize the sand sea are irregularly spaced as they extend over the pre-dune surface of Precambrian granite and schist, Tertiary aeolian sandstone, and late Tertiary–early Pleistocene fluvial deposits and calcretes. The 2–4 km wide interdune areas are covered by an angular to rounded gravel- to granule-sized lag, with rare 1–4 m high simple linear dunes and irregular barchans. There are scattered

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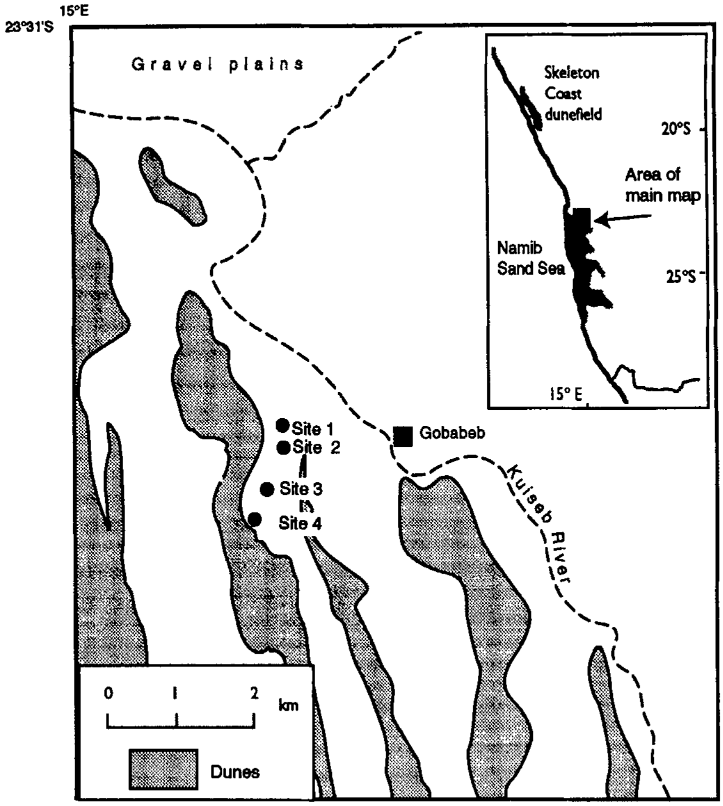

Figure 1. Location of study area (insert) on the northern margin of the Namib Sand Sea, with wind profile and surface roughness measurement sites shown

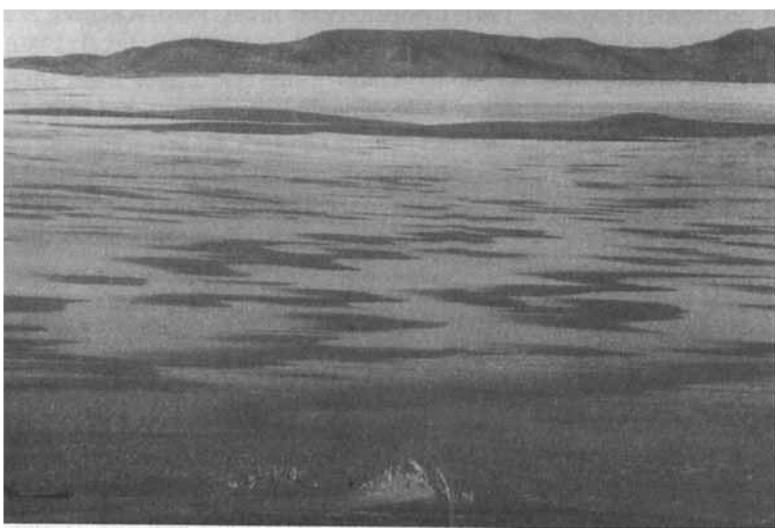

Figure 2. View of central part of sand patch zone from the linear dune to the west

exposures of the bedrock surface, especially toward the north of the area. The relief of the interdune surface in the study area is less than 1·5 m and slopes are less than 2°. To the north is a prominent escarpment up to 20 m high developed in the Tertiary-age Tsondab Sandstone. Vegetation is virtually absent in the area of concern. Isolated clumps of the perennial grass *Stipagrostis sabilicula* occur on dune plinths. The interdune area is unvegetated except after occasional heavy rains (last occurrence 1976).

Sand-moving winds in the area are from two main directional sectors (Lancaster, 1985): south to southwest (72·1 per cent of all winds >4 m s^{-1} at a height of 3 m) and NNW to ENE (19·7 per cent of all winds >4 m s^{-1} at a height of 3 m). Southwesterly winds are dominant in the spring and summer (October to April) and northeasterly winds occur in the winter (May to August).

MORPHOLOGY AND DISTRIBUTION OF THE SAND PATCHES

The sand patches are distributed in a well-defined zone 250 m wide that extends S to N for a distance of 500 m on the western side of the interdune area southwest of Gobabeb (Figures 1 and 2). The zone ends abruptly to the north. The sand patches (Figure 3) occur on a substrate that is composed of a well-rounded granule to angular gravel lag developed on a fine to medium sand that ranges in thickness from a few centimetres to a metre or more. Some areas of the granule-sized lag are formed into granule ripples (see Figure 3). The lag is derived from both nearby outcrops of white quartzite (angular particles) and fluvial deposits (well-rounded clear and frosted quartz). The sand below the lag is a mixture of grey brown fluvial and red-brown aeolian materials.

Within the sand patch zone, the spacing of the patches varies from a mean of 9·28 m at the southern end to 12·75 m in the north. The area covered by the sand patches ranges from 30–40 per cent (south) to 13–15 per cent (north). In the centre of the zone there are two small sand sheets, as much as 50 m across, which are elongated in an east–west direction. The sand sheets occupy a depression that may be a palaeochannel of the Kuiseb River.

The sand patches are generally subelliptical to subrectangular in shape, with a sharply defined rounded upwind end and a less distinct straight or 'feathered' downwind margin (Figure 4). Sand patch morphometry is summarized in Figure 4. They vary in size from less than 1 m to as much as 20 m across with a mean width of 8·14 m and a length of 12·71 m. There is a slight tendency for a preferred east to west long-axis orientation: this probably reflects the dominance of strong easterly winds in winter (May to August) when this study was conducted (1993). The sand patches are typically 0·05–0·10 m thick, with a range from 0·03 m (a single wind ripple) to as much as 0·22 m. Their area is generally less than 50 m^2.

Figure 3. Close view of sand patches on very coarse sand at the southern end of the study area (Sites 3 and 4). View to southwest. Note subdued granule ripples aligned normal to easterly winds

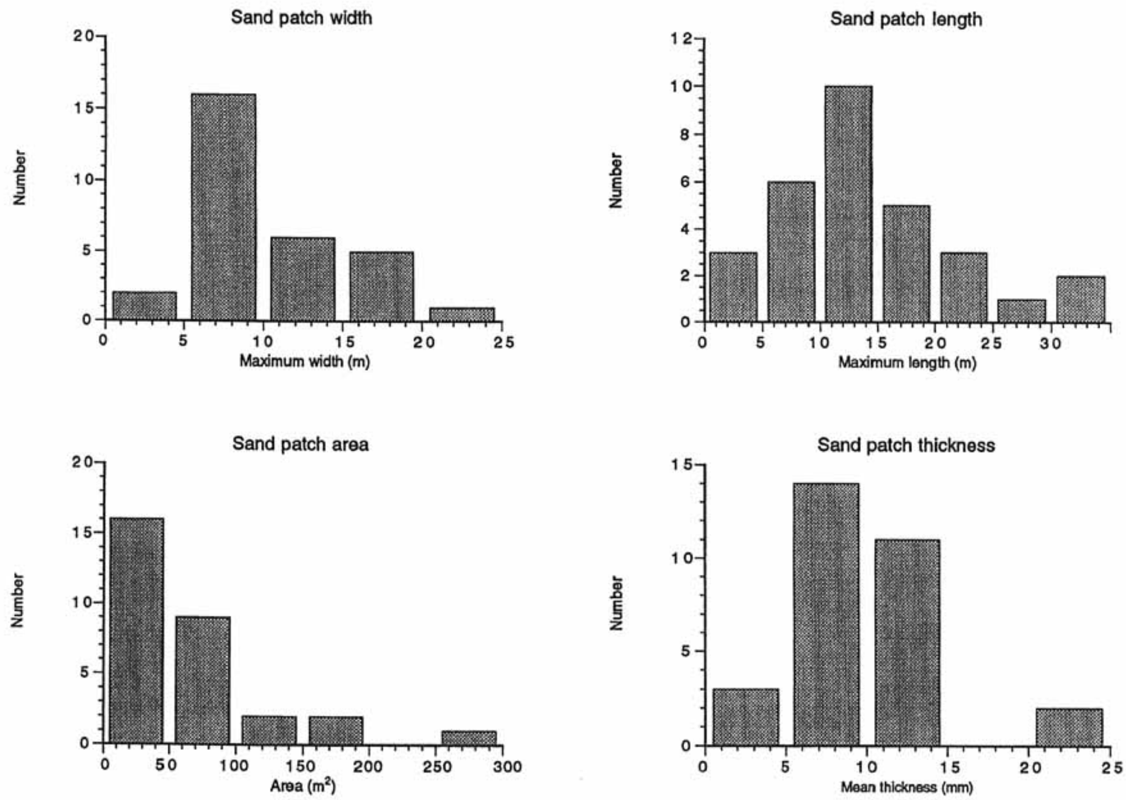

Figure 4. Morphometry of sand patches

The sand patches are composed entirely of wind ripple laminae and their surfaces are covered by wind ripples. The sand is typically fine to medium (phi graphical mean = 1·98, 250 μm), moderately sorted (phi graphical standard deviation = 0·74), and red-brown in colour. It is identical to that which makes up the plinths of the adjacent linear dunes. The upwind sides of the patches are composed of coarser sand than the downwind sides, and in some cases granule ripples occur, with the coarse grains being derived from adjacent lag deposits (Figure 3). This variation in particle size is paralleled by a change in ripple wavelength across the patches from 29 cm at the upwind (east) end, to 9·7–9·4 cm in the centre, and 10 cm at the downwind end. After periods of strong winds, areas of very coarse sand and granules extend onto the upwind parts of the patches.

The sand patches are very dynamic features. Individual examples were observed to migrate by 1·5 to 2·1 m in a 36 h period of strong easterly winds. All the patches were reshaped during a change in wind direction from south-southwest to east over a 24 h period.

Features similar to those documented here have not previously been described in the literature. The Namib sand patches most closely resemble the wind ripple protodunes of Kocurek *et al.* (1992). Similar sand patches to those documented above have been observed elsewhere in the Namib, e.g. on the Tsondab Flats (Lancaster, 1980) and on the upwind margin of the Skeleton Coast dunefield (Lancaster, 1982), on the bed of Owens Dry Lake, and in Death Valley, California (Lancaster, pers. obsv.).

SURFACE WINDS

To test the hypothesis that the sand patches form preferentially in areas of lower wind shear velocity and transport rates, boundary layer wind profiles were measured at four places along a transect oriented approximately parallel to the dominant wind (SSW to NNE) across the sand patch zone (Figure 1). These locations were chosen to be representative of the gravel-covered interdune area outside the sand patch zone (Site 1) and different lag particle sizes ranging from very coarse sand (Site 4) to granule (Site 3) and fine

Table I. Summary of site surface characteristics and mean wind profile parameters

Site	$U(2{\cdot}0\,\text{m})$ ($\text{m}\,\text{s}^{-1}$)	$u*$ ($\text{m}\,\text{s}^{-1}$)	z_0 (m)	Lag roughness density (λ)	Mean particle size of lag (mm)
1	6·44	0·30	0·00040	0·26	6·06
2	6·53	0·30	0·00042	0·32	6·72
3	7·76	0·35	0·00032	0·28	3·0
4	6·51	0.23	0·00004	0·07	1·0

angular gravel (Site 2). Table I summarizes the mean particle size and the lag roughness density (λ), or windward silhouette or frontal area per unit bed area at each site.

Wind profiles were measured using a 2 m high mast, with R. M. Young Wind Sentry cup-anemometers at heights of 0·30, 0·60, 1·20 and 2·00 m. The mast was deployed at each site for a period of approximately 24 h. The output from the anemometers was recorded on a Campbell CR-10 datalogger, with a sampling interval of 1 s and averaging period of 15 min. A subset of the data considered to be representative of sand-transporting winds was extracted in which the wind speed at the lowest anemometer exceeded 4 m s^{-1}. These data were used for estimation of wind profile parameters (summarized in Table I) using least-squares methods and checked for consistency and goodness of fit using the techniques of Bauer *et al.* (1992).

During the period in which the anemometers were deployed, winds were from south-southwest (Site 1) and easterly directions (Sites 2, 3, and 4). During much of the time, winds were observed to be transporting sand across the interdune areas. Representative wind profiles are shown in Figure 5.

Aerodynamic roughness (z_0) increases by an order of magnitude from Site 4 to Site 1 (Figure 6), reflecting the change in surface particle size and lag roughness density between these locations (Table I). Mean values of wind shear velocity ($u*$), normalized to the wind speed at 2 m, increase by up to 32 per cent relative to Site 4 in parallel with the change in both surface and aerodynamic roughness (Figure 6). The homogeneity of the surfaces in the area suggests that these variations in aerodynamic roughness and wind shear stress are representative of all wind directions.

CONTROLS ON THE DISTRIBUTION OF SAND PATCHES

The percentage of the surface covered by sand patches decreases as aerodynamic roughness of the substrate increases (Figure 7). This suggests that the sand patches tend to decrease in size and number as surface roughness increases.

For an unvegetated surface with non-erodible roughness elements, the relation between transport rates and

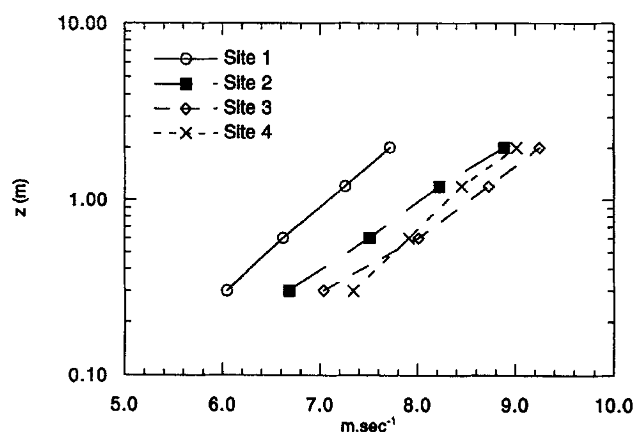

Figure 5. Representative wind profiles from each site

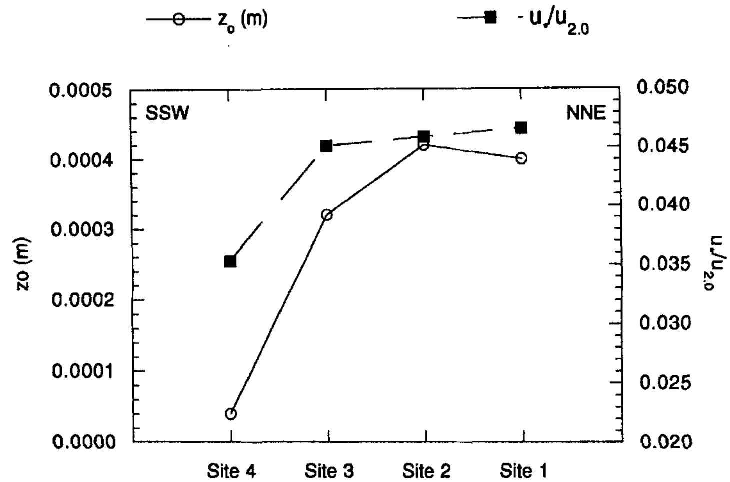

Figure 6. Variation in aerodynamic roughness (z_0) estimates across study area

the size, density and spacing of roughness elements is influenced strongly by the effect of roughness element geometry on the fluid threshold for transport (e.g. Gillette and Stockton, 1989; Iversen *et al.*, 1991; Raupach *et al.*, 1993). Both threshold shear velocity and aerodynamic roughness increases with increasing roughness density (λ), with a maximum aerodynamic roughness at $\lambda = 0{\cdot}12$ (Raupach *et al.*, 1991). The threshold for transport can be estimated in terms of particle size for transport and aerodynamic roughness as:

$$u_{*t}^2 = 0{\cdot}139\rho g d/\rho\{1 + 0{\cdot}776[\ln(1 + d/z_0)]^2\} \tag{1}$$

where d = the diameter of the grains in transport, ρ is the air density and g is the acceleration due to gravity (Greeley *et al.*, 1974).

The threshold wind shear velocity (u_{*t}) required to transport grains of the modal size found in the sand patches (250 μm) across the intervening substrate was calculated using Equation 1 and the measured values of z_0 in Table I. The estimated u_{*t} values increase by a factor of 1·80 from Site 4 (0·43 m s^{-1}) to Site 3 (0·77 m s^{-1}) and remain similar thereafter (0·79–0·80 m s^{-1} for Sites 1 and 2). Compared to a 250 μm sand surface (u_{*t} = 0·26 m s^{-1}), values of u_{*t} are 1·64 greater at Site 4, and 2·96 to 3·08 greater at Sites 3 to 1.

As shown by Greeley and Iversen (1987) and Blumberg and Greeley (1993), the transport rate depends on

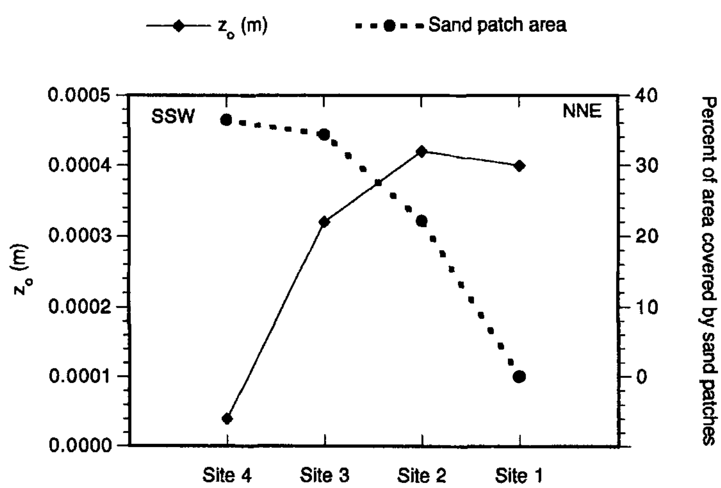

Figure 7. Relations between surface area covered by sand patches and aerodynamic roughness

the relative values of $u*$, $u*_t$, and the ratio between particle diameter and z_0. Using the measured values of $u*$ for the different sites (Table I) and the above calculated values of $u*_t$, the potential sand flux (g) was estimated using the equation of White (1979):

$$q = 2{\cdot}61u*^3\,(1 - u*_t/u*)(1 + u*_t^2/u*^2)\rho/g \qquad (2)$$

Figure 8 shows how calculated potential sand flux varies with distance across the sand patch zone for different values of wind shear velocity for a wind blowing from the SSW. At values of wind shear velocity less than $0{\cdot}70\,\mathrm{m\,s^{-1}}$, transport occurs only on the smoother sandy surfaces and ceases between Sites 4 and 3 because the threshold shear stress increases more rapidly than $u*$ on the rough surface. For values of wind shear velocity greater than $0{\cdot}70\,\mathrm{m\,s^{-1}}$, the potential flux increases from Site 4 to Site 3 and remains constant thereafter, increasing slightly again between Sites 2 and 1. The latter erosional zone corresponds to the area of sand patch dispersal.

Following principles of sediment mass conservation, areas of increasing flux with distance are erosional, decreasing flux leads to deposition, and constant flux gives rise to sediment bypassing. Figure 8 indicates that the area between the edge of the dune and Site 3 is a zone that changes from net erosion at higher wind shear velocities to deposition at lower velocities. The area between the dune plinth and Site 4 is net erosional except at wind shear velocities less than $0{\cdot}45\,\mathrm{m\,s^{-1}}$, so that the dune does not prograde over the interdune, except at the very lowest wind shear velocities. This explains why the dune and interdune areas remain distinct. The area between Sites 4 and 3 exhibits a temporal and spatial mix of erosion and deposition and corresponds to the zone in which sand patches appear to be initiated. The transport rate modelling discussed above suggests that sand is supplied to the sand patch initiation zone at lower wind shear velocities and is removed at higher velocities.

The measured wind shear velocities (Table I) are above the threshold for transport for sand surfaces much of the time, but are below that for the interdune substrate. Because the sand patches are composed of sand with a threshold wind shear velocity that is one-third of that for the substrate on which they rest, they can remain active whereas the substrate is essentially stable. Sand can move from the patches to the interdune surfaces but cannot be remobilized because the local threshold shear velocity is rarely exceeded. The sand patches therefore migrate independently of the substrate except at the highest wind velocities.

Active sand transport was, however, observed across the interdune area between the sand patches when the measured wind shear velocity was above about $0{\cdot}30\,\mathrm{m\,s^{-1}}$. This suggests that there is a large difference between the threshold wind shear velocities required for transport of sand *from* rough surfaces (fluid threshold) in which the roughness elements protect the surface, as opposed to transport *across* these surfaces with sediment being supplied from upwind (impact threshold), although there are no published wind tunnel

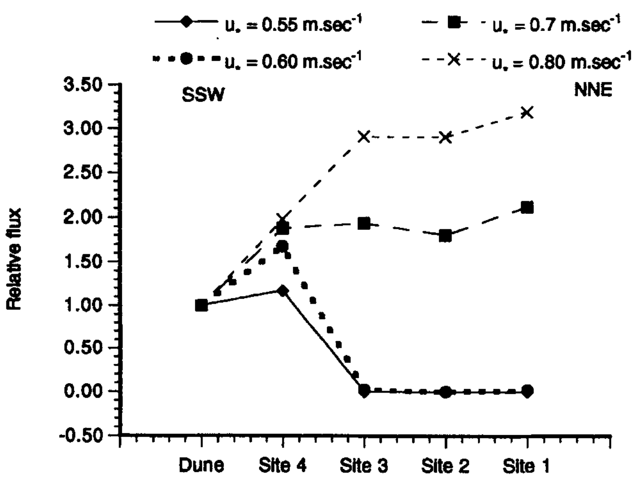

Figure 8. Variations in calculated potential sand transport by SSW winds with distance across the study area for different values of wind shear velocity

or field studies to support this hypothesis. Although relatively high wind shear velocities may be required to entrain sand from rough surfaces (Iversen *et al.*, 1991; Raupach *et al.*, 1993), transport from smoother surfaces upwind can be maintained across the rough surfaces because: (1) u_* is higher on the rougher surfaces, and (2) less momentum is extracted from the saltating grains by impacts on the large clasts, as recognized originally by Bagnold (1941). The nature of sand transport across rough and/or armoured surfaces presents an important opportunity for further field and wind tunnel studies.

CONCLUSIONS

Sand patches on the northern margins of the Namib Sand Sea are initiated in a zone of spatially and temporally fluctuating wind shear velocity on the distal plinth area of linear dunes and then migrate independently of the substrate across the interdune area. The zone of sand patches is limited in the downwind direction by an increase in wind shear velocity that corresponds to an increasingly rough surface and also by starvation sand supply from upwind areas. Limited sediment supply on the downwind margin of the Namib Sand Sea appears to be the main reason why the sand patches south of Gobabeb do not develop into dunes. Similar sand patches on the Tsondab Flats and Skeleton Coast appear to grow to dune size.

These investigations suggest that changes in aerodynamic roughness as a result of variations in substrate particle size may be an important control on dune initiation. They also highlight the need for further field studies of relations between sand flux and roughness to provide measurements of actual flux and threshold velocity on different surfaces.

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